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CARBON FOOTPRINTING

Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach

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Abstract
Purpose With increasing attention on sustainable development, the environmental and social relevance of palm oil production are now important trade issues. The life cycle assessment (LCA) study of Malaysian oil palm products from mineral soils including palm biodiesel was aimed to provide baseline information on the environmental performance of the industry for drawing up policies pertaining to the sustainable production. The share of greenhouse gas (GHG) contribution by the various subsystems in the oil palm supply chain is considered here.
Materials and methods The life cycle inventory data for the study were collected based on subsystems, i.e., gate-to-gate. The subsystems include activities in oil palm nurseries and plantations, palm oil mills, refineries, biodiesel plants and the use of biodiesel in diesel engine vehicles. Two scenarios were considered: extraction of crude palm oil (CPO) in a mill without and with a system for trapping biogas from palm oil mill effluent (POME). Inventory data were collected through questionnaires. On-site visits were carried out for data verification. Background data for resource exploitation and production of input materials were obtained through available databases and literature. Foreground data for all subsystems were site-specific data from nurseries, plantations, palm oil mills and refineries and biodiesel plants in Malaysia.
Results and discussion Using a yield of 20.7 t oil palm fresh fruit bunches (FFB)/ha, the results showed that the production of 1 t of FFB produced 119 kg CO_2 eq. The production of 1 t of CPO in a mill without and with biogas capture emitted 971 and 506 kg CO_2 eq, respectively. For the production of 1 t of refined palm oil in a refinery which sourced the CPO from a mill without biogas capture and with biogas capture, the GHG emitted was 1,113 kg and 626 kg CO_2 eq, respectively. For palm biodiesel, 33.19 and 21.20 g CO_2 eq were emitted per MJ of biodiesel produced from palm oil sourced from a mill without and with biogas capture, respectively.
Conclusions GHG contribution by the nursery subsystem was found to be minimal. In the plantation subsystem, the major sources of GHG were from nitrogen fertilizers, transport and traction energy. For the mill, biogas from POME was the major contributor if biogas was not trapped. Excluding contribution from upstream activities, boiler fuel and transport were the major sources of GHG in the refinery subsystem. In the biodiesel subsystem, activities for production of refined palm oil and methanol use were the most significant contributors.

Keywords Crude palm oil · Fresh fruit bunches · GHG · Oil palm seedlings · Palm biodiesel · Refined palm oil

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1 Introduction

Malaysia has the most mature oil palm industry in the world and land cultivated for oil palm currently stands at 4.8 million ha [Malaysian Palm Oil Board (MPOB) statistics 2008]. Much of the present oil palm plantations are cultivated primarily on land that was originally cleared for other crops such as rubber, coconut, cocoa and even coffee. Additional land requirements are met with logged over forest land or degraded land which is not needed for food production. These land areas were originally primary forests, where 50% of the original biomass has been removed by logging activities. With regard to the conversion of peat land for oil palm cultivation, for a fair evaluation of land use change, the actual amount of such land used by the Malaysian oil palm industry must be put into perspective against the amount grown on logged over forest, degraded land and on land previously occupied by other crops. There are 2.6 million ha of peat lands in Malaysia against the world's peat distribution of 450 million ha. As of 2009, about 12% of Malaysian oil palms are grown on peat land (Wahid 2009).

Palm oil is the most widely trade oil in the vegetable oil market. The major application for palm oil is in food, it can be found in one of ten products sold in supermarkets. In 2009, 45% of palm oil exports were from Malaysia (MPOB statistics 2009). The oil is internationally known for its price competitiveness and ready supply to meet growing world demand for vegetable oils. In recent years, because of the concern on depleting fossil fuels, the use of vegetable oils as renewable fuel has grown in importance.

In 2010, the MPOB completed a full life cycle assessment (LCA) study of Malaysian oil palm products from mineral soils including palm biodiesel to provide baseline information on the environmental performance of the palm oil industry. The study was conducted according to the International Standards Organization (ISO) guidelines on LCA which are found in ISO 14040:2006 and ISO 14044:2006. This paper presents the cradle-to-gate greenhouse gas (GHG) determination for processes involved in the production of palm products from the Malaysian oil palm industry in the following subsystems:

- Nursery
- Plantation
- Palm oil mill
- Refinery
- Palm biodiesel plant

In the case of palm biodiesel, the GHG was a cradle-to-grave audit. The objective was the determination of the share of GHG contribution from the subsystems and the identification of GHG sources which could be reduced to improve the environmental performance of the Malaysian palm oil industry.

2 Materials and methods

2.1 System description

The LCA for palm biodiesel production was divided into five subsystems (Fig. 1), namely, the agricultural phase where oil palm seedlings are grown in the nursery and then transplanted to the plantation [cultivation of oil palm for fresh fruit bunches (FFB)], extraction of crude palm oil (CPO) from FFB at the palm oil mill, refining of CPO to produce refined palm oil (RPO) and transesterification of RPO (palm biodiesel production). Figure 1 also shows the oil palm supply chain beginning from seedlings right down to production and consumption of palm biodiesel.

2.2 Nursery subsystem (production of palm seedlings)

The productivity of an oil palm plantation depends on many factors, the most important of which is the quality of the transplanted oil palm seedlings derived from cross pollination of selected parent palms. Subsequently, the production of high-quality oil palm seedlings is very much dependent on good nursery management and practices.

In the nursery, seedlings grown in polybags are given constant close attention during the first 10–12 months of their development. This ensures that well-developed seedlings with optimum vigor at the time of field planting can be quickly established in the field, the field immature period is minimized, and early high yields are obtained.

Germinated seeds, normally obtained from oil palm seed producers licensed by the MPOB are first sown in polybags. There are two types of nursery practice — single stage and double stage. Most oil palm nurseries practice the latter. The technique of raising seedlings in large polythene bags before transplanting them in the field is known as the single-stage nursery. The double-stage nursery consists of a prenursery and a main nursery stage. In prenursery, seeds sown in small polybags (15 cm×23 cm) are kept under the shade to protect them from direct sunlight until they are approximately 3–4 months old. In the subsequent main nursery stage, the seedlings are planted in larger polybags (30 cm×38 cm or 38 cm×45 cm) and grown without a protective shade until they are 10–12 months old and ready for planting in the plantation (Corley and Tinker 2003; Esnan et al. 2004).

All seedlings should get sufficient water of 0.5 l water/polybag/day at prenursery and 1.5–2.5 l/polybag/day at main nursery. Sprinkler systems water the seedlings twice daily, before 11:00 a.m. and after 4:00 p.m. The seedlings are supplied with nutrients and protected from pests through fertilizer and pesticide applications, respectively. Dithiocarbamate is the most commonly used pesticide in the oil palm nursery.

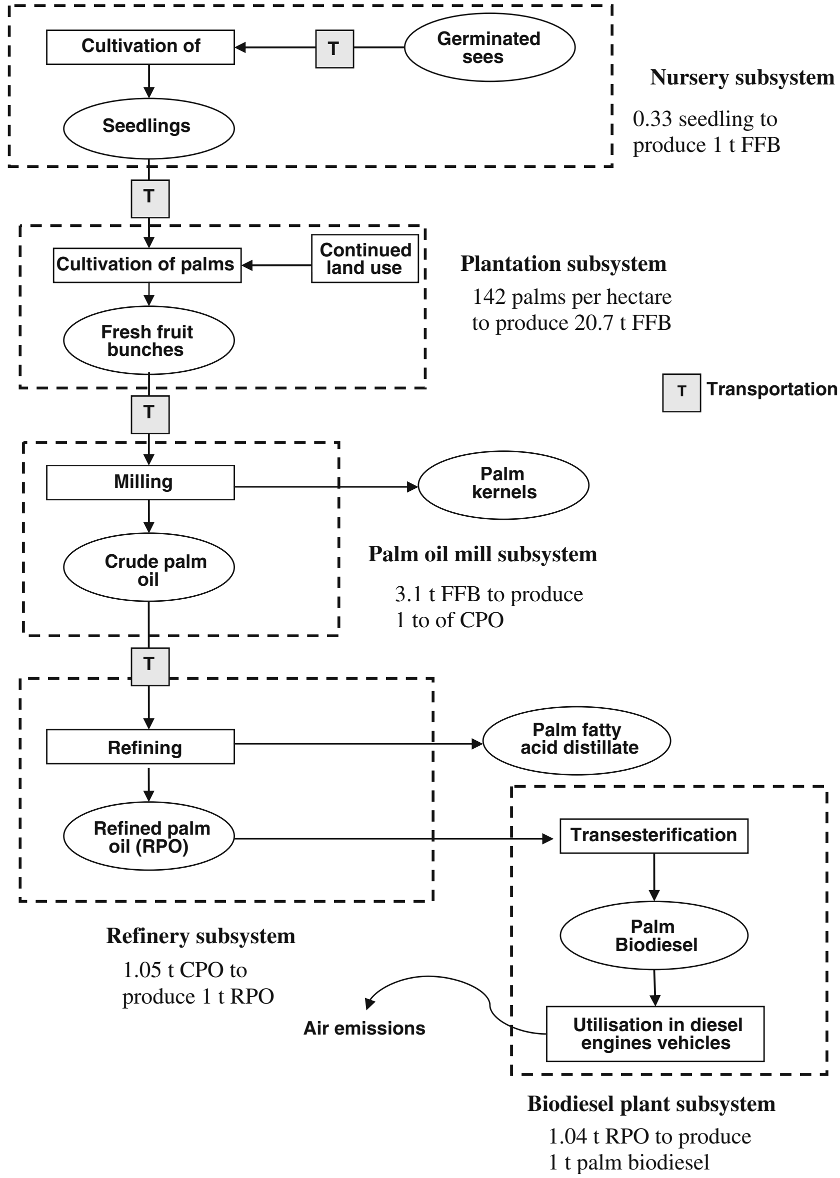

Fig. 1 System boundary of the LCA study

Culling inspections and marking of seedlings to be culled take place at 3–4, 7–8 and 11–12 months. A culling rate of about 20–25% is expected and in this study an average culling rate of 22.5% was used. Culling is necessary to avoid disease and pest infestation. Seedlings 3–4 months with characteristics, such as small unhealthy seedling, severe collate (young leaves sticking together), absence of pinnation in the youngest leaf and diseased seedlings, must be removed. Culling of 7–8 months seedling is needed following a number of observations including absence of pinnate leaves, widely or too closely spaced leaflets, erect fronds, rachis bent more than usual, leaflets not arranged systematically and small or diseased seedlings. At 11–12 months and at the time of transplanting seedlings to field, abnormal seedlings should also be rejected.

2.3 Plantation subsystem: production of FFB

In Malaysia, the oil palm planted is mainly of the *tenera* variety, a hybrid cross between the *dura* and *pisifera* varieties. The tenera variety yields about 4–5 t of CPO/ha/year and about 1 t of palm kernels. The oil palm is the most efficient oil-bearing crop in the world, requiring only 0.26 ha of land to produce 1 t of oil.

Oil palms from the nursery are transferred and planted in the oil palm plantation when they are approximately 12–13 months old. The palms are planted at a density of 136–148 palms/ha on mineral soils (assumed average of 142 palms/ha). Before the palms are planted, the soil is ploughed, compacted and a legume cover is sown. The cover crop prevents erosion and fixes nitrogen from the atmosphere in their root nodules, especially during the stage

when the palms are young. A circle, i.e., the palm circle, with no vegetation is established around each palm. The palm circle prevents encroachment of weeds. Later, when the palm matures, the circle allows easy access for harvesting and picking of loose fruits. Herbicides are applied to keep the palm circle free from weeds.

An oil palm bears its first FFB within 2–3 years and continues to do so for the next 20–25 years. Each palm produces 1 FFB every 10–21 days. Harvesting of ripe FFB is manually carried out every 10–15 days using a "pahat" (blade) when palms are short or a sickle mounted on an aluminium pole for taller palms. Normally, two fronds beneath the fruit bunch are pruned before harvesting. The pruned fronds are placed in the field between the palm rows for mulching. Detached FFB are placed by the roadside and collected later by 5- to 10-t lorries before transport to a nearby mill within 24 h.

The most common fertilizers applied in the oil palm plantation are muriate of potash, ammonium sulphate, kieserite and rock phosphate. Fertilizers are transported to plantations using lorries, while field tractors are used to transport them from the store to the estate where the fertilizers are broadcast manually.

Herbicides are usually required only when the palms are immature with canopy insufficient to prevent sunlight from reaching the weeds. Most herbicides are water-based formulations and manually applied using knapsack-spraying equipment. Insecticides are the major pesticides required for oil palm cultivation. However, their use is minimal in oil palm plantations. The application of phosphorus-based or organophosphorus insecticides for bagworm control is very site-specific and is carried out through manual trunk injection. Often, the use of insecticides and rodenticides is reduced by integrated pest management, where natural predators or bioagents, such as barn owls, BT virus, etc., are used instead of pesticides.

Replanting of oil palms is carried out when palms are 25–30 years old because of the difficulty in harvesting tall palms. Old palms also give low FFB yield. The palms are felled, chipped and left in the plantation as a nutrient source for replants. The felled palms contain about 95 t of dry weight/ha (Khalid et al. 2000, 2009) which would decompose within 2 years.

2.4 Mill subsystem: production of CPO

The FFB, delivered to the palm oil mill, are received at the FFB hoppers and transferred into sterilization cages. These cages are rolled into the sterilization chambers where the fruits are sterilized by live steam passes for duration of 90 min. This sterilization step loosens the individual fruits from the stalk or bunch and also deactivates the enzyme which causes the breakdown of the oil into free fatty acids (FFA).

The sterilized FFBs are sent to a stripper where the fruits are separated from the stalk or bunch. The bunches now free of attached fruits, known as empty fruit bunches (EFB), are normally sent back to the plantations for mulching as fertilizer substitute.

The fruits from the stripper are then sent to a digester where they are converted into a homogeneous oily mash by means of a mechanical stirring process. The digested mash is then pressed using a screw press to remove the major portion of the CPO. At this point, the CPO comprises a mixture of oil, water and fruit solids which are screened through a vibrating screen to remove as much solids as possible. The oil is then clarified in a continuous settling tank following which decanted CPO is then passed through a centrifugal purifier and desander to remove remaining solids and then sent to the vacuum dryer to remove moisture. The CPO is then pumped to storage tanks before it is sent off for export or refining at the refineries.

The nuts with the pressed mesocarp fibers are separated at the fiber cyclone and then cracked to produce kernels and shells. The kernels are shipped to kernel crushing plants to be processed into crude alm kernel oil (CPKO), while the shell and pressed mesocarp fiber are used as boiler fuel.

The main solid waste from the milling process is EFB, pressed mesocarp fiber, shell and boiler ash, while the liquid waste is palm oil mill effluent (POME). The gaseous emissions are from the boiler stack and biogas from the effluent treatment ponds.

Thus, within the palm oil milling subsystem, a number of processes take place in addition to the main process, i.e., extraction of CPO from the mesocarp of sterilized palm fruits. Besides the main products comprising CPO and palm kernel, other outflows include the production of sludge or POME during the clarification step, EFB during stripping of FFB, pressed mesocarp fiber from mechanical pressing of palm fruits, nuts from the depericarping stage and lastly shells after nut cracking to release palm kernel.

The crushing of kernels for extraction of CPKO takes place at kernel crushing plants and is therefore not accounted for in this study, as it is considered as part of a different system. The biological treatment of POME to reduce the biological oxygen demand (BOD) to 5,000 ppm for land application and to below 50 ppm for discharge to waterways results in the emissions of biogas which can be captured. This can be done by diverting the POME to digester tanks where biogas is trapped for use as fuel or flared off. The pressed mesocarp fibers and shells would have been solid waste emissions from the milling process, but instead they serve as a fuel source to fire the boilers in the palm oil mill to produce steam used for electricity generation and sterilization of FFB. EFB is used as mulch or compost to substitute fertilizer. The treated POME can also be used as fertilizer substitute. The recycling of solid wastes. such as mesocarp

fiber and shell for use within palm oil mill subsystem. establishes close loops for these outputs from the palm oil mill, while the EFB and POME which are recycled in the plantation are considered open-loop processes.

In this study, the method selected for partition of coproducts was allocation based on weight. Palm kernel and the excess palm shells are considered as coproducts and a weight allocation of 61% CPO, 25% palm kernel and 14% shell was used. System boundary expansion is conducted for EFB and POME which are recycled in the plantation as fertilizer substitutes. The savings as fertilizer substitute for both EFB and POME comes under the FFB production stage. The pressed mesocarp fiber and shell are burnt as fuel in the palm oil mill boiler, while the excess shell is sold as fuel for other biomass boilers. However, the credits for the use of excess shell elsewhere are not included in this study, as it is out of the system boundary and so allocation is carried out for shells. The credits for displacing fuel with the use of the captured biogas are also not included. What is included is the credit of capturing the biogas.

2.5 Refinery subsystem: refining of CPO

There are two different methods for refining CPO — physical refining and chemical refining. In this study, CPO refining is modeled using the physical refining process because almost all of the RPO produced in Malaysia are obtained using physical refining. Only a handful of Malaysian refineries carry out chemical refining which involves the neutralization of FFA in degummed CPO with caustic soda followed by an additional water-washing step to removed soap resulting from the neutralization process.

Material inputs for the refining of CPO are phosphoric acid for degumming and bleaching earth for adsorptive cleansing. Spent bleaching earth containing an average of 20% retained oil is obtained when the degummed, bleached oil is filtered before the subsequent step of refining, i.e., deacidification and deodorization stage.

Energy for oil processing is met by electricity from the grid and fossil fueled boilers, which produce steam from municipal water. Steam is used to heat the oil during degumming and earth bleaching, while live steam is injected into the deodorizers during stripping of free fatty acid and other undesirable volatiles from the oil in the deacidification and deodorization step.

Liquid waste from the refinery include waste water which is discharged after treatment, while palm fatty acid distillate (PFAD) is the coproduct resulting from the stripping of the more volatile fatty acids from the oil during the deacidification and deodorization step to produce low free fatty acid oil. Data collected showed that an average of 45 kg PFAD is produced for every ton of CPO processed. Thus, a weight allocation of 95.5:4.5 of RPO to PFAD was used for this study.

2.6 Biodiesel plant subsystem: production and use of palm biodiesel

The transesterification of RPO produces palm biodiesel which is used for diesel engine vehicles. Many pathways are available to produce biodiesel in the form of alkyl ester. A continuous transesterification of RPO with methanol in the presence of sodium hydroxide has been selected for this study, because most of the commercially available biodiesel is produced using this process. It is the most economical process as it takes place at relatively low operating temperature and pressure, has a high conversion of more than 98% and involves direct conversion to methyl ester in a relatively short reaction time.

The transesterification process used is a three-stage reaction process followed by washing, drying and polishing of the reaction products. RPO is thoroughly mixed with excess methanol and catalyst and heated to the reaction temperature, and the mixture is fed into the continuously stirred tank reactor. The glycerol formed is separated from the methyl ester phase. These steps are repeated in the second and third reactors to ensure maximum conversion of acylglycerols to methyl esters. Excess methanol and efficient removal of glycerol are necessary to achieve maximum yield.

On completion of the reaction, the methyl ester phase is heated in a plate heat exchanger and sent to a series of flash tanks, where unreacted methanol is removed by evaporation. In a parallel stream, the glycerol phase is heated in a plate heat exchanger and sent to a series of flash tanks to evaporate the residual methanol before storage. The combined methanol vapor is sent to a rectification column for purification. The recovered methanol is recycled to the methanol-fed tank for reuse.

The methyl ester is washed with hot water in two vertical washing columns to remove residual glycerol, methanol and soap with separation of wash water after each column. A centrifugal separator after the second column ensures efficient separation of wash water and thorough removal of the impurities.

The methyl ester is dried under vacuum to reduce its water content to within the specified limits of biodiesel standards. The final product is cooled in a heat recovery system and with cooling water before it is sent to storage via two alternately working polishing filters.

For this study, the biodiesel and glycerol were allocated based on weight at a ratio of 89.3:10.7. The palm biodiesel was evaluated in bench endurance tests by Mercedes Benz, Germany. This exhaustive and comprehensive field trial involved 30 buses which covered more

than 10 million km in total (each traveling more than 300,000 km — the lifetime of the engine as recommended by engine manufacturers).

2.7 Data collection and quality

Inventory data were collected from 21 nurseries, 102 plantations, 12 palm oil mills, 11 palm oil refineries and 2 biodiesel plants. These represent data from 7% of nurseries, 25% of land under oil palm cultivation, 5% of palm oil mills, 20% of the refineries and 11% of the palm biodiesel plants in Malaysia.

The inventory data obtained from 102 plantations covered an area of 1.1 million ha. This represents approximately 25% of the area under oil palm cultivation in Malaysia. The plantations surveyed consist of 93.7% mature (3- to 25-year-old palms) and 6.3% immature area (1- to 2-year-old palms) from private and government estates and of organized smallholders from all over the country. Data collected were for a period of 3 years. The FFB yield was estimated by averaging the yield from mature and immature palms (zero yield taken for immature areas) over a life cycle of 25 years. Correction factors were used to account for zero FFB yield in the first 3 years and the gradual increase in yield until reaching a plateau at around 16–20 years before the decrease toward the end of lifecycle. Information obtained from questionnaires included the number of palms per hectare as well as the FFB yield per hectare per year.

The collected data were averaged to derive a set of generic data representing Malaysian palm products supply chains based on mineral soils. The results from the life cycle inventory (LCI) were subsequently used to assess the GHG emissions of the palm oil supply chain from the nursery to the intermediate and final products — seedlings, FFB, CPO, RPO and palm biodiesel.

Background data which include information on generic materials, such as water, energy and transport, were collected from published sources or proxies, e.g., same operation but in another country. Wherever possible, local data were used. In the absence of available data, information was sourced from public databases, Ecoinvent database, published literature and intelligent estimates drawn from reference to similar systems or products. Main data sourced from literature and databases include land use change carbon, manufacture of fertilizers and pesticides and water treatment. Data for pesticide emissions during application in nurseries and plantations were determined using a worst case approach where emissions of applied active ingredients were considered equally distributed to air, water and soil (Schmidt 2007). Calculation of pesticide emissions were based on the EPA approach (EPA 1994).

Most of the foreground data for each unit process were collected directly from oil palm growers, millers, refiners and biodiesel producers through questionnaires which were developed specifically for data collection. Inputs at the agricultural stages, i.e., nursery and plantation, were apportioned over the typical economic life span of oil palms set at 25 years. Compliance with geographical coverage for data collection was adhered to by collecting data for the palm oil supply from different regions in West (Peninsular) Malaysia and East Malaysia (Sabah and Sarawak). For each data set, the period during which the data were collected and how the data were collected were documented. The data validation procedure was carried out by on-site visits, on-site measurements, communication and discussions via e-mail and telephone and interviews to verify the reliability of collected data. Data gaps were filled by information obtained through literature, public databases or calculated using published models.

2.8 Assumptions and cutoff rules

It is to be noted that for calculation of GHG emissions from the nursery and plantation subsystems, a 25-year lifetime was taken for the oil palm. In addition, 142 palms/ha, producing 20.7 t FFB/year, were used in the calculation. Several inflows and outflows in the supply chain were found to be difficult, if not impossible, to quantify. Hence, certain criteria for exclusions were used. As a starting point, the mass criterion was used, and material inputs with more than 1% (>1%) to the processes were included. Despite this predefined cutoff criterion based on mass, every attempt has been made to collect all material and energy inputs to the five subsystems that can be environmentally relevant, regardless of their mass contributions.

In the case of the plantation subsystem, the intermediate flows of inputs (release from decomposition of biomass, including dying back biomass) and outputs (uptake of nutrients from soil in the standing biomass, excluding harvested biomass such as biomass from felled palms during replanting, biomass in pruned fronds, etc.) are assumed to be equal over the lifetime of oil palm. Decomposition was not determined because coproducts brought back to the plantation were not considered. Only the use of inorganic fertilizers were considered in this study.

In this study, allocation of process inputs and outputs based on the products' mass is used. The rationale in using mass allocation is that physical portioning is most consistent as it contains the least uncertainties. In contrast, the economic value of palm products fluctuates from year to year resulting in the need for frequent updating of data. Notwithstanding this, system expansion was carried out for POME and EFB, which are recycled in the plantations as fertilizer substitute. Further details on the assumptions and allocations can be

found in Halimah et al. (2010), Zulkifli et al. (2010), Vijaya et al. (2010), Tan et al. (2010) and Puah et al. (2010).

2.9 Products and functional unit

The GHG emissions to be assessed depend on the stage of the oil palm industry product supply chain evaluated. In the case of this particular LCA study, the first product was the oil palm seedling, followed by FFB from matured palms cultivated from oil palm seedlings, CPO extracted from FFB, RPO resulting from the physical refining of CPO and lastly palm biodiesel from transesterifcation of RPO. Thus, the LCA of the Malaysian oil palm industry including palm biodiesel covers the five subsystems shown in Fig. 1.

The functional units used for each product would depend on the function of the system investigated so as to provide the product for subsequent use. Accordingly, in the nursery where the function is to produce seedlings for oil palm cultivation, the functional unit is one seedling. The plantation produces FFB for CPO extraction, the mill produces CPO for processing into RPO, the refinery processes CPO into RPO, and the biodiesel plant processes RPO into biodiesel for use in vehicles. Thus, the appropriate functional units for the subsystems are one seedling and 1 t each of FFB, CPO, and RPO, respectively, while that for palm biodiesel was the use 1 MJ of palm biodiesel in vehicles. For the sake of clarity, the coefficients linking the functional units used in each subsystem were included in Fig. 1.

2.10 Modeling for this study

In the LCA study associated with this GHG emissions study, the oil palm supply chain was modeled using System for Integrated environMental Assessment of PROducts (SimaPro, version 7) and the Ecoindicator methodology (Goedkoop and Spriensma 1999). The Ecoinvent database provided in SimaPro was used to determine GHG emission factors, especially when background data were not available.

3 Results and discussion

As this study was grouped into different subsystems, the share of contribution from the identified subsystems (see Fig. 1) are given and examined. For the calculation of GHG emissions, the emission factors for electricity and water were from the Malaysia Life Cycle Inventory Database (MY-LCID) developed by the Standards and Industrial Research Institute of Malaysia (SIRIM; SIRIM 2010). In the case of land and sea transport, emission factors were sourced from the Ecoinvent database, which was also the source for emission factors for fuel oil combustion. It is to be noted that all distances for transport of products were considered as half of a round trip. Vehicle loads were full-load weights and a 50% load factor was used with the vehicles operating at full capacities on their journey to their destination and making empty return trips.

3.1 Nursery subsystem: production of oil palm seedling

Table 1 shows the average inputs for production of a single seedling based on data obtained from 21 oil palm nurseries. The determination of the required number of seedlings and land in the nursery to provide 142 palms/ha in a plantation on mineral soils is shown in Table 2. Based on the LCI data in Table 1, production of one seedling emitted 0.05 kg of CO_2 (carbon dioxide) equivalent. In general, this subsystem contributed insignificant amounts to GHG emissions, accounting for only 0.01% of the share of GHG in the production of 1 t of FFB (Fig. 2).

3.2 Plantation subsystem: production of FFB

The agricultural operation for the oil palm includes activities related to cultivation of oil palm in the field during the mature and immature phases of the palms. The FFB yield applied is the average yield obtained from the survey and the characteristics of the plantation for this study is shown in Table 3.

The total amounts of applied fertilizers in oil palm plantations were calculated as the average of 2 years

Table 1 LCI for the production of a single oil palm seedling (Halimah et al. 2010)

Input	Amount
Electricity (kWh)	0.006 (0.22 MJ)
Diesel (L)	0.004 (0.15 MJ)
Polybag (kg)	2.10E-03
Water (L)	1.5
Fertilizer	
N (kg)	5.10E-04
P_2O_5 (kg)	2.60E-04
K_2O (kg)	2.10E-04
Thiocarbamate (kg)	1.12E-05
Pyrethroid (kg)	3.54E-06
Organophosphate (kg)	2.00E-05
Dithiocarbamate (kg)	9.61E-05
Unspecified Pesticide (kg)	1.35E-06
Urea/sulfonylurea (kg)	2.17E-05
Glyphosate (kg)	8.90E-06
Transportation (tkm)	
Van (<3.5 t) B250	6.47E-09

Table 2 Determination of the required quantity of oil palm seedlings and land in the prenursery and main nursery in order to provide palm densities in the plantation at 142 palms/ha on mineral soil

Required quantity of palm seedlings grown on mineral soils in the main and prenursery	
Required palms per hectare in the plantation (palm density)	150 palms
Loss at planting	8 palms
Loss of seedlings in the main nursery	10%
Required seedlings in the main nursery	167
Loss of seedlings in the prenursery	15%
Required seedlings in the prenursery	196
Calculation of the required land	
Prenursery	Land used for 196 seedlings
Prenursery (palm density: 563,000 oil palm seedling/ha, duration: 3 months)	0.87 m^2 year
Main nursery	Land used for 167 seedlings
Main nursery (palm density: 12,500 oil palm seedling/ha, duration: 10 months)	250.5 m^2 year
Total land use per replanting	251 m^2 year
Total land use relating to 1 year out of 25 years	10 m^2 year

immature and 23 years mature palms. The real fertilizer input from the survey was relatively low (especially N fertilizer at 72.2 kg N/ha/year) compared to the recommended input, because fertilizer input was less during the first 2 years of the immature palm. In addition, fertilizer application is stopped at year 22 (a practice in most the plantations), 3 years before replanting. Fertilizer recommendation is higher, because it is derived from fertilizer trials carried out during the prime age of the oil palm, i.e., 7–15 years old. In actual practice, fertilizer application rate is dependent on a number of factors including yield potential, age of palm, nutrient balance, field conditions and soil types. For older palms, yields are low and when they are about to be replanted, fertilizer is not applied, and the palms utilize nutrient reserves in the soil and oil palm trunk. Many of the smallholders apply smaller amounts of fertilizer due to economic reason. In high yield potential areas, i.e., more than 28 t FFB/ha/year, the fertilizer rate can be as high as 124 kg N/ha/year, although the average recommended fertilizer rate is 110 kg N/ha for mature areas. The amount of fertilizer applied for immature areas (1–3 years) is 48 kg N/ha/year, while at the end of the palm cycle (21–15 years), fertilizer rate is reduced to an average of 53 kg N/ha/year (Tarmizi 2010; FAO 2004).

In this subsystem, continued land use was considered, i.e., replanting of oil palms. Thus, there is no land use change from conversion of primary or degraded forest or other tree crops to oil palm. Emissions from the plantation were determined following a number of references (Schmidt 2007; IPCC 2006; Ecoinvent Center 2004). Table 4 shows the LCI data for the calculation of the GHG emission, and Fig. 2 shows the share of GHG emissions from this subsystem. The total amount of GHG emitted from this system was found to be 119 kg CO_2 eq. Fig. 2 shows that for production of 1 t of FFB, a major portion of the emissions was from N fertilizer (48.7%), and this was followed by emissions (32.0%) resulting from the manufac-

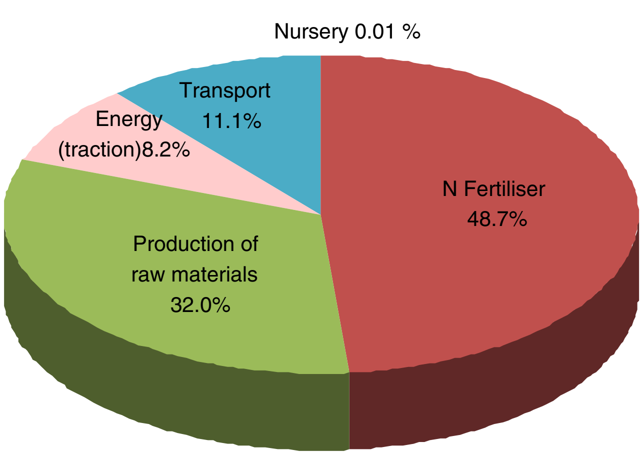

Fig. 2 Share of GHG emissions for production of 1 t of FFB

Table 3 The characteristics of the plantations used in the study (Zulkifli et al. 2009)

Plantation characteristics	
FFB yield (t/ha/year)	20.7
Planting density (palm/ha)	142
Soil characteristics	Mineral soils
Plantation lifetime	25 years
Number of plantations	102
Total area	1.1 million ha (93.7% mature and 6.3% immature)

Table 4 LCI for the production of 1 t of FFB

Input	Amount
Energy use	
Diesel; agriculture machinery (L)	2.37
Material use	
Oil palm seedling (transplant)	0.33
Ammonium sulfate (kg)	8.05
Urea (kg)	0.41
Ammonium nitrate (kg)	0.76
Ammonium chloride (kg)	0.72
N from compound, mixture (kg)	1.16
N fertilizer application (kg)	3.49
Muriate of potash (kg)	11.6
Fertilizer K_2O from compound, mixture (kg)	4.5
Total K_2O applied (kg)	11.5
Phosphate rock (kg)	6.55
Fertilizer P_2O_5 from compound, mixture (kg)	0.64
Total P_2O_5 applied (kg)	2.8
Glyphosate (kg a.i)	0.338
[Sulfonyl]urea compounds(kg a.i)	0.148
Bipyridylium compounds (kg a.i)	0.104
Pyretroid compounds (kg a.i)	0.0215
Organophosphorus compounds (kg a.i)	0.064
Carbofuran (kg a.i)	0.035
2,4-D,dimethylamine salt (kg a.i)	0.031
Pesticide unspecified (kg a.i)	2.087
Transport	
FFB to mill; lorry (tkm)	50
Fertilizer from port to plantation; lorry (tkm)	5.1
Pesticides from port to plantation; lorry (tkm)	0.15
Emissions to air (kg/t FFB)	
NH_3	0.324
N_2O	0.19
NO	0.06
N_2	0.516
Glyphosate	0.0667
Metsulfuron-methyl	0.019
Glufosinate ammonium	0.265
Paraquat	0.022
Emissions to water (kg/t FFB)	
NO^{3-}	2.58
PO_4^{3-} (leached out and run off)	0.046
Glyphosate	0.0667
Metsulfuron-methyl	0.019
Carbofuran	0.0045
Glufosinate ammonium	0.265
Paraquat	0.022
Emissions to soil (g/t FFB)	
Glyphosate	0.0667
Metsulfuron-methyl	0.019
Carbofuran	0.0045
Glufosinate ammonium	0.265
Methamidophos	0.0056
Paraquat	0.022

ture of raw materials (fertilizers, pesticides). This suggests that the mitigation options would be in the reduction of N fertilizer application, if possible, and green procurement of raw materials (e.g., organic fertilizer or N fertilizer produced using modern technology to reduce N_2O emissions).

In this study, no land use change was considered. If tropical forests were converted to oil palm plantations, carbon loss would exceed the carbon sequestration during the life cycle (25 years) of the oil palm. On the other hand, when oil palm plantations replace degraded land, carbon sequestration exceeds carbon loss and the plantation is now a net carbon sink.

Based on a literature review on the use of diesel in plantations, internal transport and machinery (Wicke et al. 2008; Reijnders and Huijbregts 2008; Nikander 2008), GHG emissions are in the order of 180–404 kg CO_2 eq/ha/year, while emissions related to the use of inorganic fertilizers and pesticides are between 1,000 and 1,500 kg CO_2 eq/ha/year, giving a total emission of 1,180–1,904 kg CO_2/ha/year. If the FFB yield is set at 20 t/ha, the total GHG emission would be between 59 and 96 kg CO_2/t FFB, which is lower than the 119 t CO_2/t FFB reported in this study. The higher value reported here can be attributed to the inclusion of also transport of raw materials to the plantation.

3.3 Palm oil mill subsystem: production of CPO

In the palm oil mill, the inputs to produce CPO are FFB, power consumption from turbine and grid, diesel consumption, boiler fuel, water consumption for boiler as well as the milling process and steam input to turbine for sterilization and digestion of fruits. The outputs are biomass wastes, POME, gaseous emissions from the stack, biogas from POME and ash from the boiler. The LCI data shown in Table 5 were used for calculation of the share GHG for this subsystem. Quantification of biogas emission from 1 t of POME was based on the amount reported by Ma et al. (1999) and this is shown in Table 6. Two scenarios were used — the first was based on a mill without a system for biogas capture from POME and the second on a mill with 85% biogas capture. It was found that the production of 1 t of CPO in a mill without and with biogas capture emitted 971 and 506 kg CO_2 eq, respectively. As shown in Fig. 3, the major sources of GHG were biogas from POME

Table 5 LCI for production of 1 t CPO (with weight allocation; Vijaya et al. 2010)

Parameter	Amount
Fresh fruit bunches (t)	3.10
Power consumption from turbine (MJ)	224.08
Power consumption from grid (MJ)	1.76
Diesel consumption for mill (MJ)	100.33 MJ
Transportation of diesel to mill (tkm)	0.54
Fuel used in boiler	0.36
Mesocarp fiber (t)	0.09
Shells (t)	
Boiler water consumption (t)	1.57
Water for processing (t)	2.17
Kernels (t)	0.41
Mesocarp fiber (t)	0.00
Shells (t)	0.23
Empty fruit bunches (EFB; t)	0.71
Palm oil mill effluent (POME; t)	1.86
Methane gas (kg)	22.21
CO_2 from POME pond (kg)	36.04
Boiler ash (t)	0.01
Steam input to turbine (t)	1.62
Steam input for sterilization (t)	1.56
Flue gas from stack	
Particulate matter (kg)	0.12
CO (kg)	0.04
CO_2 (kg)	41.28
SO_x (kg)	0.0006
NO_x (kg)	0.07
Wastes	
EFB	Mulching
POME	Treated as fertilizer
Excess mesocarp fiber and shells	Sold as fuel
Boiler ash	Land application

followed by the agriculture stage of the oil palm. However, this is only seen in the first scenario, i.e., without biogas capture. The GHG contribution was reversed in the second

Table 6 Biogas emissions from anerobic ponds

1 t POME emits	28 m^3 biogas (Ma et al. 1999)
Biogas	65% CH_4 and 35% CO_2
CH_4	18.2 m^3
CO_2	9.8 m^3
Density	CH_4=0.656 kg/m^3
	CO_2=1.977 kg/m^3
CH_4	11.94 kg
CO_2	19.40 kg

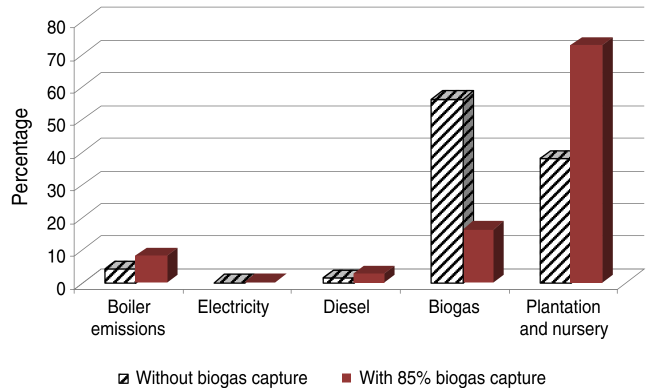

Fig. 3 Contribution of GHG emissions from the mill subsystem showing reduction from mill as a result of biogas capture from POME

scenario. The other contributor, insignificant in comparison with biogas from POME and the agriculture stage, was that from boiler emissions.

According to Schmidt (2007) who did a study on the palm oil supply chain up to the refinery, a value of 860 kg/t CPO was obtained when biogas is captured in the palm oil mill. This figure is higher than the figure of this study (506 kg CO_2 eq/t CPO). In Schmidt's study, peat soil emission was included in his case study and this could account for his higher GHG emission. The value for biogas from POME used in Schmidt's study was also based on the value reported by Ma et al. (1999) which was 28 m^3/t POME.

3.4 Production of RPO

An amount of 1.05 t of CPO is required for the production of 1 t of RPO (Table 7). Using data from Table 7, the GHG emission for the production of 1 t of RPO was found to be 1,113 kg CO_2 eq if CPO is supplied from a mill without a system for capturing biogas, and this value is reduced to 626 kg CO_2 eq if the CPO is from a mill which captured biogas. Mortimer et al. (2010) reported that the total GHG emission associated with the production of 1 t of RPO was 1,136 kg CO_2 eq, which is just 23 kg more than the value reported for the scenario where CPO is sourced from a mill without biogas capture.

Tan et al. (2010) reported that the greatest environmental burden arose from the feed material used for production of the RPO, i.e., CPO. This was followed, albeit insignificant in comparison to contribution by the feed, by boiler fuel combustion and transport of materials. The results suggested that potential mitigation measures for reduction of GHG would be to address these three inflows into the system. Figure 4 shows that share of GHG emissions by inputs (excluding CPO) in the refinery subsystem. The major contribution in descending order was boiler fuel,

Table 7 Inventory for production of 1 t of RPO beginning and ending at refinery gate (Tan et al. 2010)

Input item	Unit	Amount
Electricity	kWh	11.94
Boiler fuel	MJ	476.91
Boiler fuel	kg	11.09
Water	L	113.39
Crude palm oil	t	1.05
Phosphoric acid	kg	0.59
Bleaching earth	kg	9.11
Road transport		
CPO transport (distance) from mill to refinery (28-t truck)	km	120
Transport of CPO to refinery	tkm	126
Fuel oil transport (distance) from supplier to refinery (28-t truck)	km	500
Transport of fuel oil to refinery	tkm	5.545
Phosphoric acid transport (distance) from chemical plant to refinery (28-t truck)	km	500
Transport of phosphoric acid to refinery	tkm	0.30
Bleaching earth transport (distance) from chemical plant to refinery (16-t truck)	km	100
Transport of bleaching earth to refinery	tkm	0.91
Spent Bleaching earth transport (distance) from refinery to landfill(16-t truck)	km	15
Transport of spent bleaching earth to landfill	tkm	0.17
Sea transport		
Phosphoric acid sea transport (distance) from Europe to Malaysia	km	15,000
Transport of phosphoric acid to Malaysia	tkm	8.85
Bleaching earth sea transport (distance) from Asia to Malaysia	km	3,000
Transport of bleaching earth to Malaysia	tkm	27.33
Output item		
Waste water	L	42.16
Palm fatty acid distillate	kg	45.62
Spent bleaching earth	kg	11.09
Waste water BOD	kg	1.12
Waste water COD	kg	3.26

transport of raw materials, waste water, spent bleaching earth and lastly electricity. The results suggested that the potential mitigation measures for reduction of GHG would be to address the inflows of CPO, boiler fuel and transport into this subsystem. One option, which would produce a huge reduction in GHG emission, would be to source CPO from mills which implemented a system for biogas capture. As for the use of boiler fuel, GHG reduction could be through the use of renewable energy. Transport GHG emission could be reduced by improving transport logistics by routing delivery of materials, e.g., CPO, for the shortest distance between the supplier and the refinery.

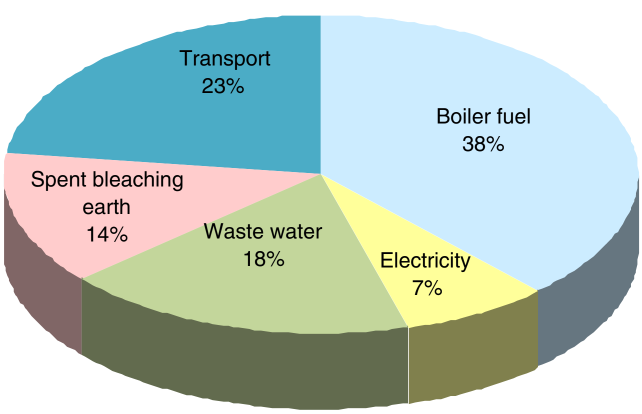

Fig. 4 Percentage contribution of GHG emissions from the refinery subsystem (excluding contribution from CPO~91.5%)

3.5 Production of palm biodiesel

In this study, no transportations of RPO and palm biodiesel were considered, as biodiesel plants were assumed to be located in the same premises as refineries. In addition, there were no inventory data available on the carriage of palm biodiesel from the plant to distribution terminals and subsequently to diesel kiosks to be used in diesel engine vehicles.

Puah et al. (2010) reported that the major contributor toward environmental impact for the processing step and use of palm biodiesel in diesel engine vehicles was

Table 8 LCI based on functional unit of use of 1 MJ palm biodiesel (Puah et al. 2010)

Input/output	Unit	Amount
Raw materials		
RBD palm oil	$MJ/MJ_{biodiesel}$	1.006
Methanol	$MJ/MJ_{biodiesel}$	0.055
Sodium hydroxide	$kg/MJ_{biodiesel}$	0.0001
Hydrochloric acid	$kg/MJ_{biodiesel}$	0.0004
Utilities		
Electricity	$MJ/MJ_{biodiesel}$	0.0022
Water	$kg/MJ_{biodiesel}$	0.009
Steam	$MJ/MJ_{biodiesel}$	0.0144
Instrument air	$Kg/MJ_{biodiesel}$	0.00008
Products		
Biodiesel	MJ biodiesel	1.00
Glycerol	$kg/MJ_{biodiesel}$	0.003
Wastewater	$kg/MJ_{biodiesel}$	0.009

emissions from the use of palm biodiesel in diesel engine vehicles and the use of methanol in the transesterification process. Based on the two scenarios of with and without biogas capture from POME and the LCI data given in Table 8, it was shown that the raw materials needed for producing biodiesel, i.e., RPO, contributed an exceedingly large portion of the share of GHG emissions (Fig. 5). Other contributions from utilities were found to be insignificant and negligible.

From Table 8, the GHG emission for production of 1 MJ of palm biodiesel was calculated and found to be 33.19 and 21.20 g CO_2 eq/MJ biodiesel, if CPO were produced in a mill without and with biogas capture, respectively. In comparison, Mortimer et al. (2010) gave a value of 41 g CO_2 eq/MJ biodiesel. Since no mention of biogas capture was made in the report by Mortimer et al., it is assumed that the CPO is supplied by a mill without biogas capture.

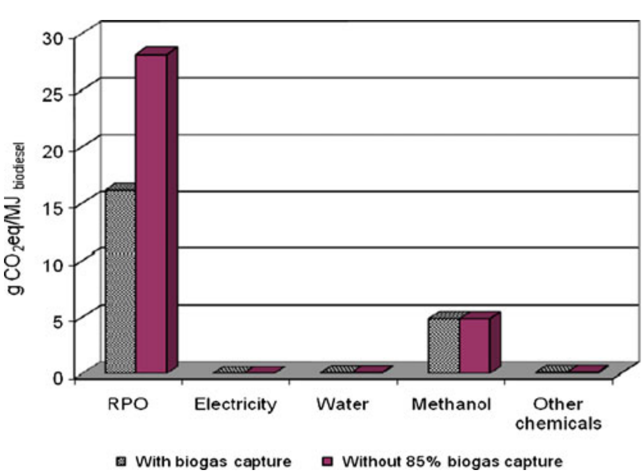

Fig. 5 Share of GHG emissions for production of 1 MJ biodiesel

4 Conclusions

A decidedly significant amount of the GHG emissions associated with the whole life cycle of the oil palm supply chain was from the agriculture stage in the plantation. Emissions were mainly from the use of fertilizers. Another source of GHG was from the biogas (methane) in the POME released in the milling process.

Earlier papers (Halimah et al. 2010; Zulkifli et al. 2010; Vijaya et al. 2010; Tan et al. 2010; Puah et al. 2010) have reported that climate change was one of the most significant impacts of the oil palm supply chain. Calculation of GHG emissions from the subsystems showed that the production of 1 t of FFB produces 119 kg CO_2 eq. The production of 1 t of CPO in a mill without biogas capture emits 971 or 506 kg CO_2 eq if the mill captured 85% of the biogas produced from POME. For production of 1 t of RPO in a refinery which sourced the CPO from a mill without biogas capture, the GHG emitted is 1,113 and 626 kg CO_2 eq if biogas is captured. In the case of palm biodiesel, 33.19 and 21.20 g CO_2 eq were emitted per MJ of biodiesel produced from palm oil sourced from a mill without and with biogas capture, respectively. It was also found that the processing step from transesterification of RPO to palm biodiesel contributes to 5.1 g CO_2 eq/MJ of biodiesel produced, which is a small fraction over its entire life cycle.

5 Conclusions

Efforts should be focused on reduction of GHG emissions within the control of the managers of the defined subsystems in the oil palm supply chain. Production of raw materials for use in the oil palm industry is beyond the management of the oil palm industry, although one mitigation option is through the implementation of green procurement.

Salient recommendations for reduction of GHG can be summarized as follows:

- Reduction of inorganic fertilizers by applying more organic nitrogen fertilizer. Returning the nutrient-rich slurry from the POME treatment to the field or applying compost (EFB+POME) as fertilizer, thereby reducing inorganic fertilizer application.
- Judicious application of fertilizers using precision application based on diagnosis of nutrient requirements from soils and foliar analyses.

- Biogas capture from POME anaerobic ponds as a source of renewable energy.

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